Spin Transistor

Spin Transistor

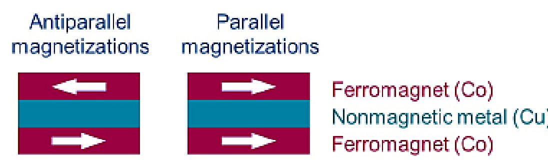
- The spin transistor uses ability of electrons to naturally exhibit one of two states of spin: known as "spin up" and "spin down", unlike ordinary transistor, which operates on an electric current, spin transistors operate on electrons on a more fundamental level; it is essentially the application of electrons set in particular states of spin to store information.

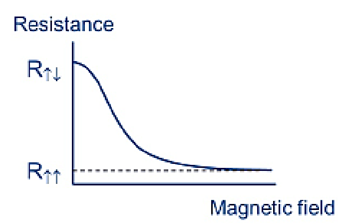
Benefits of Spin Transistor

- Smaller size
- Less power because E of spin change < E to push charge around.
- Higher speeds Magnetic RAM leading to no ‘boot-up’ waiting period when powered on.
- Non-volatile information, Spins don’t change when power is turned off.

GMR “Giant Magnetoresistance”

- GMR is a 2 layer of ferromagnetic material (cobalt) between them a non-magnetic material (silver).
- Resistance depends on the magnetization direction of ferromagnetic.
- Low resistance for Parallel alignment, High resistance for Antiparallel alignment.
- Magnetization direction can be controlled by applying external magnetic field.
- Electron spin direction controls the magnetization direction by applying magnetic field.
- Applications of GMR
    - One bit memory cell in MRAM
    - Hard disk drives
    - MEMS



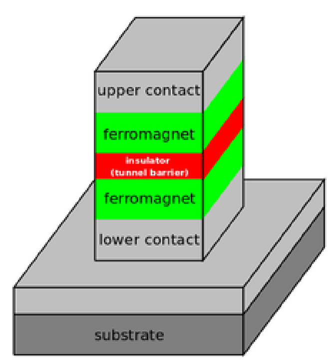


Spin Valve

- It is the concept of using electron spin direction to control the resistance, like a valve.

Magnetic Tunneling Junction

- The Nonmagnetic material is replaced with an insulating barrier.
- Electron tunneling is controlled through resistance change by magnetization direction.
- Further change in resistance can be done by changing the width of the tunneling barrier.

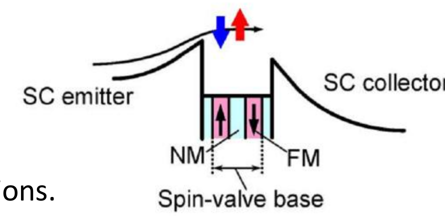


Spin Transistor Design Structure

1. Potential-Effect Spin Transistors

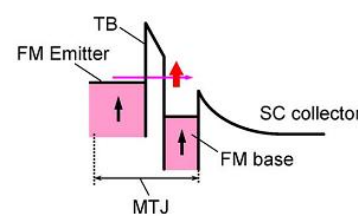
a. Hot-Electron Spin Transistors

I. SV Base



- Thermionic-emission-type emitter.
- Spin valve base.
- Emitter & Collector barriers are formed by Schottky junctions.
- Hot electrons are injected from emitter to base by thermionic emission.
- Electrons aligned **Parallel** for **Parallel** SV base magnetization.
- Electrons aligned **Antiparallel** for **Antiparallel** SV base magnetization.
- Mean Free Path "MFP"
  - It is the average distance traveled by the electron between successive impacts.
  - Higher resistance means shorter MFP and vice versa.
- Parallel magnetized SV leads to longer MFP, higher output current.
- Antiparallel magnetized SV leads to shorter MFP, lower output current.
- Disadvantages of SV Base:
  - Low output current due to very low current transfer ratio. $\alpha = \left(\frac{I_C}{I_E}\right) \sim 10^{-4}$
  - For use in active IC then current gain must be $\beta > 1$ while $\beta = \frac{\alpha}{1-\alpha}$
  - $\alpha > 0.5$ **for** $\beta > 1$, while $\alpha \sim 10^{-4}$, so SV can't be used in active IC.

II. MTJ E-B Junction

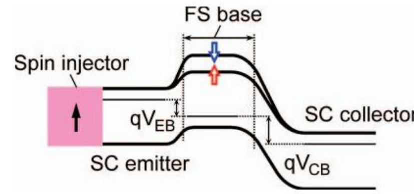


- Tunneling-emission-type emitter.
- Magnetic tunnel Junction (MTJ) is used for E-B Junction.
- Emitter & Collector barriers are formed by Schottky junctions.
- Spin polarized electrons are injected from emitter to base through the tunnel barrier.
- The MFP depends on the magnetization configuration of the Emitter-Base MTJ.
- Parallel magnetized E-B Junction leads to longer MFP, higher output current.
- Antiparallel magnetized E-B Junction leads to shorter MFP, lower output current.
- Tunneling-emission increases α slightly but it is still insufficient. $\alpha \sim 10^{-3}$

Conclusion for SVT & MTT

- Both can't be used in active IC's due to their low transfer characteristics.
- They can be used in spin injector/detector for a semiconductor with high efficiency.

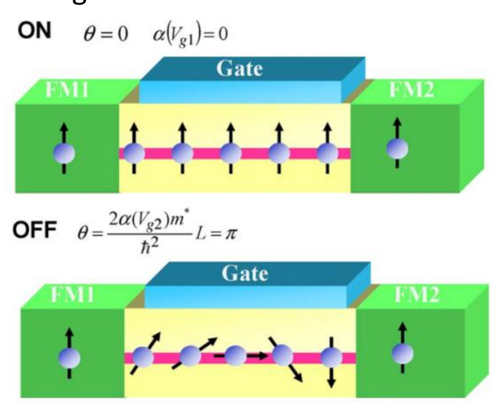
b. Bipolar Spin Transistors "MBT"



- Uses a p-type ferromagnetic semiconductor for base.
- E-B and B-C junctions are ferromagnetic pn junctions.
- BJTs can achieve a very high α.
- Magnetization Configuration between the emitter spin injector and base
  - Parallel: "high collector current"
  - Antiparallel: "low collector current"
- Disadvantages of MBT:
  - Very high carrier density of ferromagnetic semiconductors causes α to degrade.
  - High power consumption due to the high power-delay product of BJT.

2. Operating Principle of the Spin-FET

- **Operating Principle**
  - **Spin FET**
    - Switching operation can be achieved by spin precession.
  - **Spin MOSFET**
    - Magnetization configurations of the source and drain are used to modify output currents.
  - The spin precession angle Δθ is given by $\Delta\theta = \frac{2\alpha m^*}{\hbar^2} L$
    - α is the strength of Rashba spin-orbit interaction.
    - m^* is the effective mass of electron.
    - $\hbar$ is the Planck's constant.
    - L is the channel length



- The key idea of the spin-FET is that the spin orientation can be controlled by the gate electric field instead of the external magnetic field. When the Rashba spin-orbit interaction is zero as shown in top figure, the injected spin polarized carrier is transported without spin precession. Then, drain current is expected since the transported carrier has the same orientation as the FM drain electrode. To make OFF-state, the injected spin polarization in SM 2DEG channel can be reversed by the gate voltage which can tune the Rashba spin-orbit interaction parameter.

Spin Transistor Applications

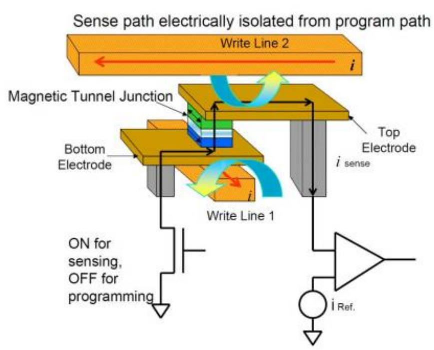
Magnetoresistive RAM (MRAM)

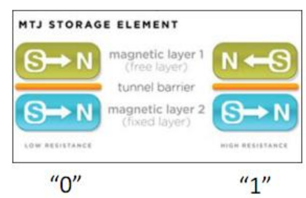
Structure

- Consists of a standard MOSFET connected to an MTJ.
- The MTJ has two FM layers, one free to flip and the other is pinned (fixed).
- Depending on the state, the resistance can be high or low

Write Operation

- Passing high current into the cell causing the free magnetic layer to switch direction thus switching the state from zero to 1 and vice versa.
- The switching can also be done through thermal process.





MRAM Advantages & Issues

- Advantages
    - Nonvolatile RAM
    - Fast read & write
    - No refresh
    - Non-destructive read
- Practical Issues
    - Need to pass high enough current during the read process to determine the correct state; this current can cause magnetic switching and thus unintentional write.
    - Ambient temperature can also cause the free magnetic layer to switch unintentionally.

Hard Drive Read Heads

- GMR based magnetic sensors are used in hard drives.
- GMR effect is used to sense the orientation of the magnetic domains on the hard drive to determine if the bit is 1 or 0.